Effects of climate change on Kincaid's lupine

2013

Report to the Oregon Department of Fish and Wildlife

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Institute for Applied Ecology

PREFACE

This report is the result of an agreement between the Institute for Applied Ecology (IAE) and a state agency. IAE is a non-profit organization dedicated to natural resource conservation, research, and education. Our aim is to provide a service to public and private agencies and individuals by developing and communicating information on ecosystems, species, and effective management strategies and by conducting research, monitoring, and experiments. IAE offers educational opportunities through internships. Our current activities are concentrated on rare and endangered plants and invasive species.

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Cover photograph: Kincaid's lupine and the common garden experiment

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EXECUTIVE SUMMARY

Kincaid's lupine (*Lupinus oreganus*), a rare legume found in prairies and oak savannas, is listed as threatened by the US Fish and Wildlife Service and the Oregon Department of Agriculture, and endangered by the Washington Department of Natural Resources. Extensive land development and alteration in the prairies of western Oregon and southwestern Washington have relegated remaining populations to small, isolated patches of habitat. The historic habitat of *L. oreganus* may continue to become more inhospitable given that climate models predict temperature increases and decreased precipitation in the Pacific Northwest. We used an experimental common garden to test for interactions between genotype and microclimate to identify management considerations which may be necessary for long-term adaptation to climate change. Treatments included ambient (no treatment) and experimental manipulations of the microclimate to simulate cooler (shading plots) and hotter (warming plots) temperatures. After one year of growth, results suggest:

1. Seed source was found to significantly affect height of Kincaid's lupine in the common garden,
2. Both seed source and treatment (ambient, warming, shading) were found to affect number of leaves of Kincaid's lupine, though the interaction of these two factors was not significant. Though some seed sources did show differences in number of leaves by treatment, these effects were not consistent across all sources. Plants from Coburg Ridge, Oak Basin (both Eugene East recovery zone), and Wren (Corvallis West recovery zone) all tended to have greater number of leaves in the warming treatments.
3. Survivorship of Kincaid's lupine was dependent upon seed source, but not by treatment.
4. Reproductive effort was highly variable between seed source at the time of monitoring.
5. We observed differences between seed sources in germination time, where species from the southern end of the range germinated far earlier than the rest.

Results of this study help inform management decisions regarding appropriate seed source populations and site selection for future population introduction efforts. In addition, this study has been an innovative approach to involving students and volunteers in learning about climate change and conservation research.

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INTRODUCTION

Figure 1. Kincaid's lupine (*Lupinus oreganus*)

Kincaid's lupine (*Lupinus oreganus*, Figure 1), a rare legume found in prairies and oak savannas, is listed as threatened by the US Fish and Wildlife Service and the Oregon Department of Agriculture, and endangered by the Washington Department of Natural Resources. Extensive land development and alteration in the prairies of western Oregon and southwestern Washington have relegated remaining populations to small, isolated patches of habitat. Habitat loss is likely to continue as private lands are developed; over 90% of Kincaid's lupine populations occur on private lands. Establishing new populations on protected lands is key to long-term recovery (USFWS 2010) for both Kincaid's lupine and the Fender's blue butterfly (*Icaricia icarioides fenderi*).

Kincaid's lupine recovery efforts are focused on the historic habitats of this species: south-facing prairies and oak savannas. However, we have observed that lupines growing in shade at forest margins are often more vigorous than lupines in full sun (A. Thorpe, *personal communication*). The historic, open habitat of *L. oreganus* may continue to become more inhospitable given that climate models predict a temperature increase of 1 to 2°C by 2040 with another 3 to 4° C by 2080 and decreased effective precipitation in the Pacific Northwest (Doppelt et al. 2009). Within the past century, the Pacific Northwest has already experienced an increase in temperature from 0.5-1.5 °C (Parson 2001). Climate models suggest a trend of warmer, drier summers and wet winters, which could benefit both native species adapted to summer drought and exotics that inhabit a wide distribution and tolerate a range of conditions (Bachelet et al. 2011). These climate changes may be particularly detrimental to populations of rare species already stressed by a lack of connectivity and gene flow, and by competition with exotic species. There are varying projections related to the effects of climate change on nutrient dynamics, which could greatly affect the presence and persistence of nitrogen fixing species such as lupine. Pfiefer-Meister and Bridgham (2007) found that under warmer, wetter winter conditions soil respiration would increase and plant available nitrogen would decrease; which could result in a competitive advantage of nitrogen fixing species. Other sources have suggested projected climate changes may increase nitrogen availability due to nitrogen deposition, thus eliminating the main competitive advantage of nitrogen-fixing species like lupines and increasing the potential for exotic species (Suddick et al. 2012). Despite these unknowns, a number of factors suggest that the targets for recovery of Kincaid's lupine are achievable. Seed collection efforts have already begun in several large populations in each recovery zone, protected sites with suitable habitat for establishment of new populations have been identified, and we have developed a large body of knowledge on the biology and ecology of this species (Wilson et al. 2003). By determining how projected changes to climate affect establishment and survival of Kincaid's lupine, we can increase the potential for long-term persistence of introduced populations.

We used an experimental common garden to test for interactions between genotype and microclimate to identify management considerations which may be necessary for long-term adaptation to climate change. Treatments included ambient (no treatment) and experimental manipulations of the microclimate to simulate cooler (shading plots) and warmer (warming plots) temperatures. These treatments were meant to replicate past, present, and future climate conditions. This common garden experiment will enable us to determine if there is population differentiation in response to treatment, seed source, or both. We seek to answer the following questions:

1. Are populations from the southern end of the range of Kincaid's lupine better adapted to climate conditions projected for the future (increase in temperatures), due to the warmer climate they already occupy?

2. Are plants from northern populations better adapted to shaded (cooler) microclimates?

3. Do plants in the middle extent of its range (Willamette Valley) respond more favorably to ambient conditions?

Results of this study will help inform management decisions regarding appropriate seed source populations and site selection for future population introduction efforts. In addition, this study has been an innovative approach to involving students and volunteers in learning about climate change and conservation research.

METHODS

In 2011, seed was obtained from eight Kincaid's lupine populations, ranging from the southern extent of its range to the north Willamette Valley (Figure 2, Table 1). The Wren and McMinnville seeds were obtained from private land owners. In addition, seed from a population in Washington state was obtained in summer 2012, thereby expanding seed sources used in this common garden to those from the northern extent of its range (Figure 2). Long term mean temperatures and precipitation differed between seed recovery zones (Figure 3, WRCC 2008).

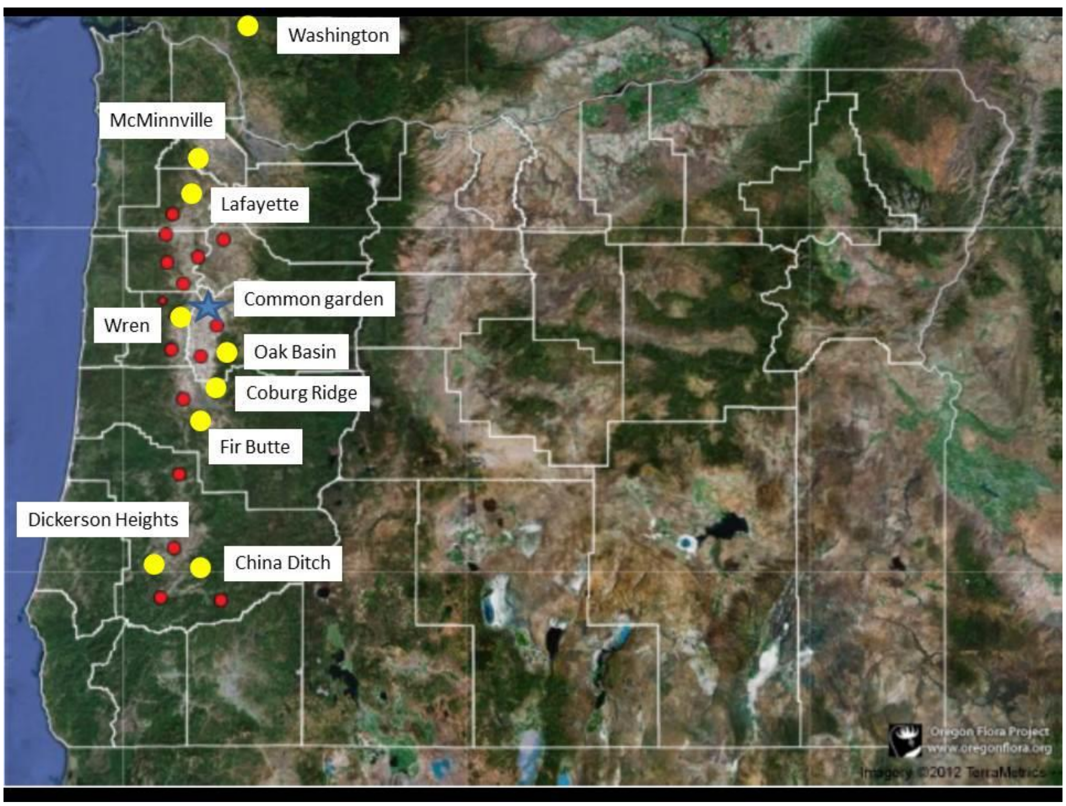

Figure 2. Kincaid's lupine seed sources used in this experiment (yellow), the common garden location (blue star), and other occurrences (red) in Oregon.

Table 1. Seed sources used for common garden experiment. Washington plants were added in 2013.

Seed source	Recovery Zone	Habitat	Exposure	# of plants
China Ditch	Douglas County	Road cuts and slopes	Partial shade	120
Dickerson Heights	Douglas County	Saddle	Partial shade	120
Fir Butte	Eugene West	Valley	Full sun	120
Oak Basin	Eugene East	Foothills	Full sun or partial shade	76
Coburg Ridge	Eugene East	Foothills	Full sun or partial shade	104
Wren	Corvallis West	Valley	Full sun	120
Lafayette/ODOT	Salem West	Valley	Full sun	120
McMinnville	Salem West	Valley	Full sun	120
Washington	Southwest Washington	Valley	Full sun	120
Total				1079

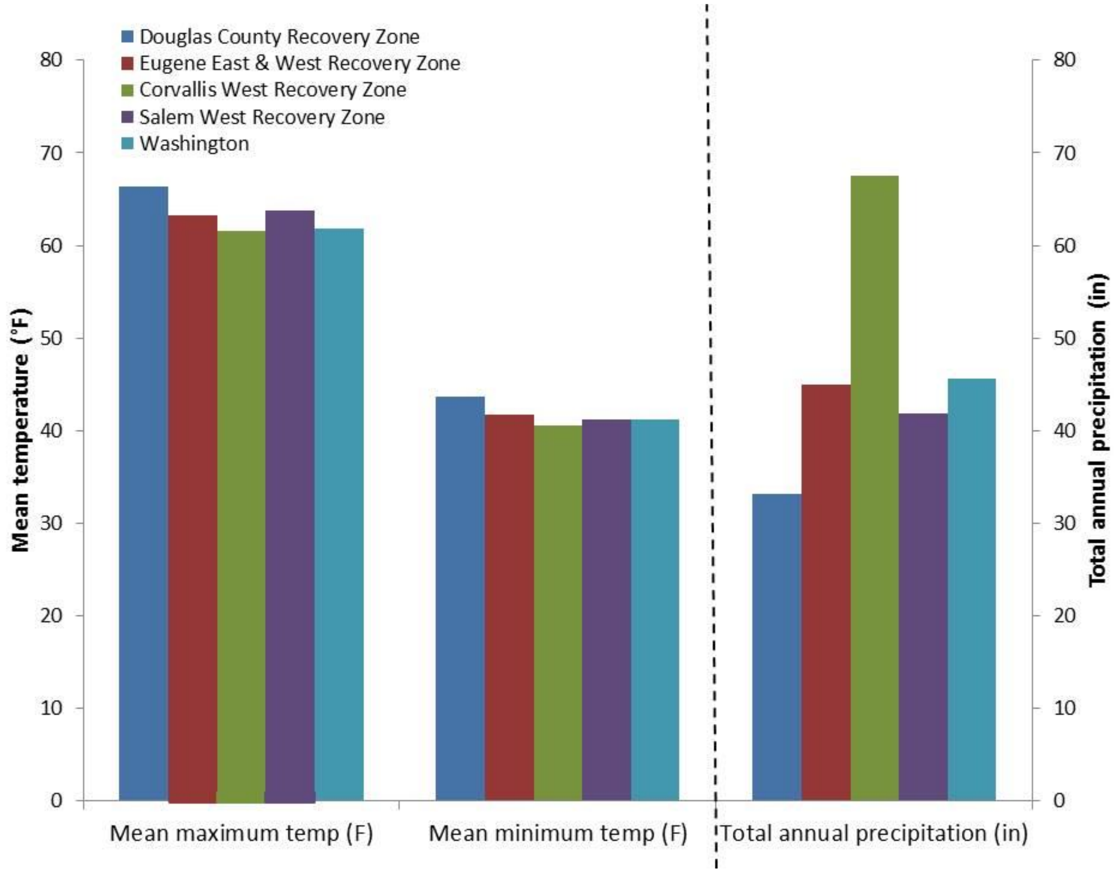

Figure 3. Annual means for maximum temperature (F), minimum temperature (F) and total annual precipitation (in) from weather stations located within the recovery zones 1965-2013.

Propagation

Figure 4. Kincaid's lupine seedlings from Dickerson Heights

In the winter of 2012, over 2900 seeds from eight populations of Kincaid's lupine were propagated in the greenhouse producing over 2000 plugs (goal of 120 plants per seed source). Seeds were scarified using a small mechanical scarifier, and were placed in cold stratification (4°C) for four weeks to promote germination. Seeds were transferred to the greenhouse where they were maintained at 21°C during the day and 13°C at night with 14 hours/day of artificial light provided by a Sun System 3 - 400 HPS bulb for one month. After the majority of seeds had germinated (approximately one week), seedlings were moistened with distilled water and the radicles were dipped in rhizobium inoculum prior to potting into a custom soil mix of potting soil and perlite in SC10 superpots (Figure 4). Plugs were fertilized twice in the first 10 days of potting using a low nitrogen fertilizer (2,4,4), and once every two weeks thereafter, and were watered every three days. Plugs were monitored for survival by seed source.

To control for fungus gnats, all pots were sprayed with a solution of predatory nematodes and were topped with sterilized sand. After two months in the greenhouse, plugs were placed outside for two weeks to harden-off prior to out-planting in April 2012. Seeds from Washington were obtained in 2012, propagated in early 2013, and added to the existing common garden in April 2013.

Experimental Design

We set up a common garden of experimental plots at the OSU East Farm, Field 6 (Figure 5). This site had been a research field for perennial grasses, and was sprayed with a grass specific herbicide [Fusilade™, (Fluazifop)] in the fall of 2011 in order to control some of the grass dominance prior to establishing our experiment. A total of thirty 10 ft^2 plots were established, with 10ft buffers in between. Thirty plots were arranged in a grid consisting of 10 replicates of three randomly assigned treatment types: ambient, shading, and warming. The ambient plots were left open to the surrounding environment. Both shading and warming plots were made of 10'x10'x3' PVC frames; the shading plots were covered with highly permeable shade cloth (40%) and the warming plots were covered with clear 4mm greenhouse-grade plastic sheeting with holes 1in^2 holes to allow precipitation to permeate through (Figure 6). Experimental plots were created and maintained through the combined efforts of IAE staff and numerous volunteers including middle and high school students from the City of Corvallis Youth Volunteer Corps. Within each treatment plot, temperature (C°) and relative humidity (%) were monitored at lupine canopy height every 30 minutes using hygrochron ibuttons (Maxim Integrated [e.g. Thorpe 2010]). Belowground temperature was monitored every 15 minutes using thermochron ibuttons (Maxim Integrated). Precipitation in each plot (ml) was measured weekly using rain-gauges created from recycled 2 liter bottles. In November of 2012 and in February 2013, plots were sprayed with glyphosate (Aquamaster™), a broad-spectrum herbicide to combat issues with invasive clover. All Kincaid's lupine were dormant at this time.

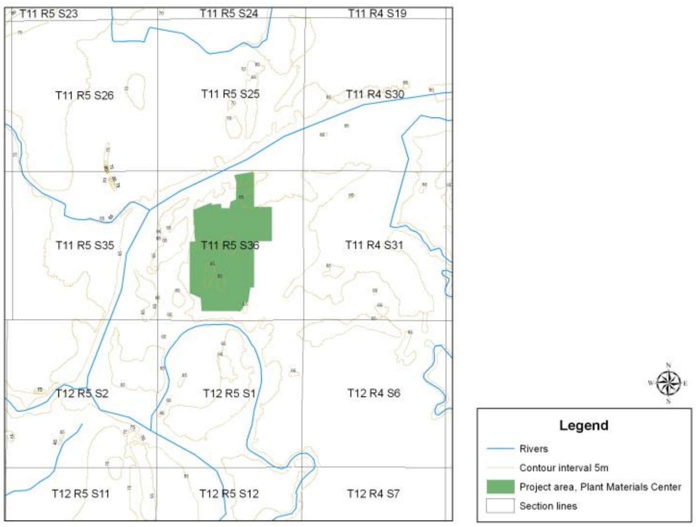

Figure 5. Location of the common garden research plots at the OSU East Farm.

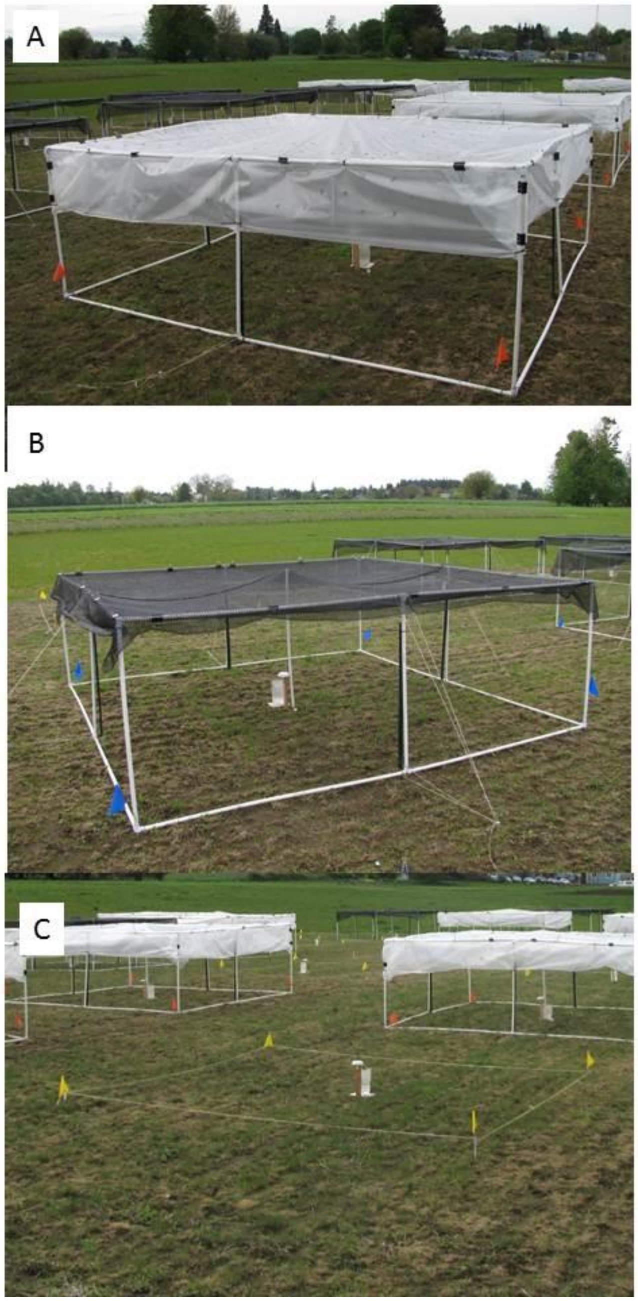

Figure 6. Experimental plots at the common garden. A. warming, B. shading, and C. ambient.

Plugs were out-planted into a grid of 36 plugs per plot, their position randomly defined within a 6 x 6 ft grid with 1 ft spacing in April 2012. Each plot contained at least 4 plugs from each of the eight seed sources; plugs from Washington were added to the common garden in April 2013 (four plugs in each plot). With the additions, a total of 1079 plugs were planted (Table 1). Due to differences in the available seed and propagules from Oak Basin and Coburg Ridge, the number of plants per plot from these sources were fewer than from the others (Table 1). Plugs were planted with a dibble, were watered in, and were covered with native soil to initiate establishment. Volunteers assisted with planting and weekly plot maintenance including supplemental watering and weeding when needed.

Mortality associated with initial establishment was monitored in early May 2012 and those plants were replaced with individuals from the same seed source at that time. In total, 184 plants out of 959 were replaced (approximately 20%) due to initial mortality. Monitoring of lupine growth and survivorship occurred in June 2012 and 2013; we monitored each plant by measuring the length of the longest leaf (cm) and counting the number of leaves. In 2013, the number of racemes (flowering stems) was counted on reproductive plants during the time of monitoring and were then clipped and discarded to deter the crossing of plants from different recovery zones.

Data Analysis

We used measurements of Kincaid's lupine height (length of the tallest leaf; cm) and number of leaves as indications of growth of the species. For all analyses we used data from 2013 and omitted the Washington seed source as it was the first year of growth. We used 2-factor ANOVA (R Development Core Team 2009) to test for the response of height of Kincaid's lupine, using treatment (warming, shading, and ambient) and seed source as fixed factors. Due to differences in number of plants per seed source we used type II sums of squares and unweighted means. When a significant main factor effect was found, a single factor ANOVA was used to test for differences in mean size of Kincaid's lupine for that factor. Differences between seed sources were tested using the Tukey HSD test for multiple comparisons.

We tested for effects of seed source and treatment on the response of number of leaves of Kincaid's lupine using a general linear model with a quasipoisson distribution due to over-dispersion. Survivorship (binomial, from 2012 to 2013) was tested with a logistic regression with a negative binomial distribution using seed source and treatment as predictors. Models were evaluated using an analysis of deviance chi-square test. Reproductive effort (number of racemes at the time of monitoring) was totaled by seed source and proportions of reproductive plants were calculated.

We summarized rainfall of experimental plots by calculating mean monthly precipitation (ml) for each treatment. Aboveground and belowground temperature (°C) and % relative humidity were summarized into mean monthly values using R (R Development Core Team 2009). Standard error of the mean was also calculated for these summaries. When gaps in the data occurred due to ibutton malfunction, values were averaged across treatment plots. Greenhouse mortality and germination were also monitored and summarized.

RESULTS

Propagation

The Institute for Applied Ecology has had great success with greenhouse propagation of Kincaid's lupine, and we used great care in ensuring survivorship among our plugs. During propagation, we noticed differences between seed sources at a very early life-stage (Figure 7). Seeds from China Ditch and Dickerson Heights (Douglas County recovery zone; far southern populations) both germinated much earlier than all other sources, with the majority of germination occurring during cold stratification. For the other seed sources, most germination occurred once the seeds were taken out of cold stratification and placed in the greenhouse to acclimate. This could be a local adaptation to warmer temperatures and an earlier growing season experienced in the Douglas County area (Figure 3).

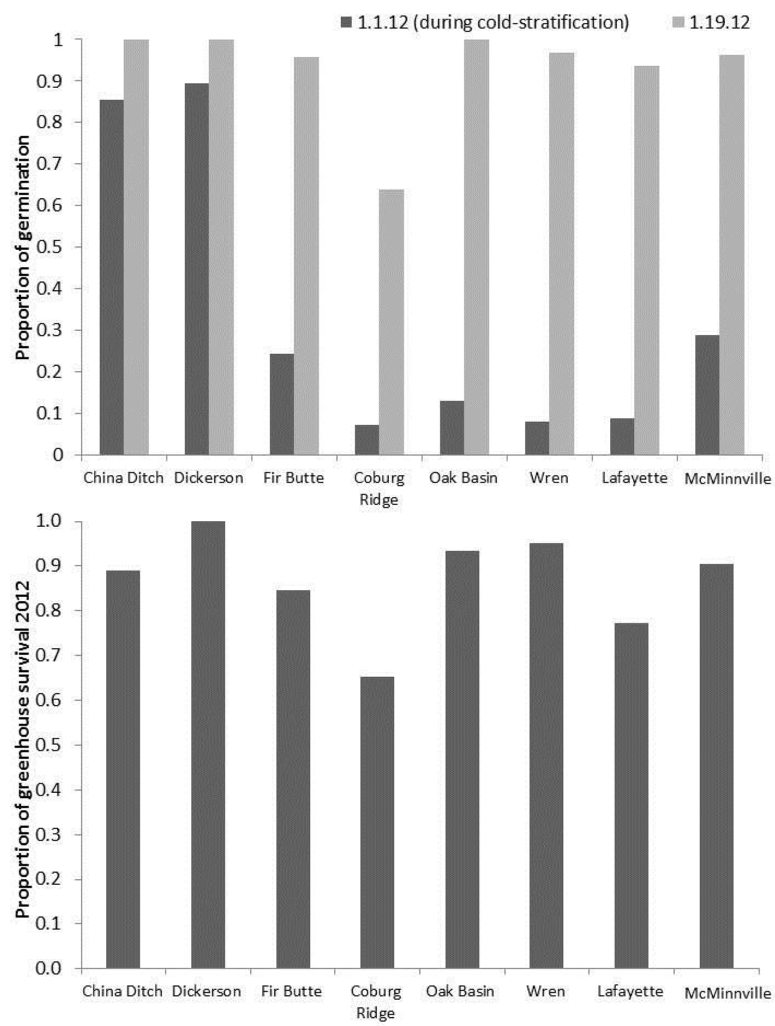

Figure 7. Proportion of seeds that germinated during cold-stratification (January 1, 2012, dark bars) and those that germinated after January 19th, 2012, light bars (above). Proportion of plugs that survived the greenhouse until out-planting in May 2012 (below).

We also observed differences between seed sources in survivorship in the greenhouse (Figure 7). Plants from Coburg Ridge had the lowest proportions of survivorship, followed by those from Lafayette (Figure 7, below). These differences could be due to the seed quality at each site. Coburg Ridge experienced a low seed year, and, of those, many of the seeds were unfilled. The presence of unfilled seeds tended to contribute to fungal infections during cold stratification, which could detrimentally affect even filled, healthy seeds.

Differences in microclimate of experimental plots

Though we aimed to have uniform precipitation across all plots, the warming and shading structures created a barrier to natural precipitation resulting in variable levels across those plots. In general, shading and ambient plots were the most similar in precipitation (means =123 ml and 120 ml, respectively), and both experienced more precipitation on average than the warming plots (mean=64 ml). While the warming structures had holes cut in the greenhouse plastic to allow for precipitation to enter the plots, it was difficult to get an accurate reading because readings were largely dependent on the placement of the rain gauge at that time. Due to this, precipitation readings for the warming plots could both over- or under- representing actual precipitation values experienced. In general, precipitation was variable over the course of the study (Appendix I). The common garden experienced two long periods of summer drought with no precipitation in 2012 and 2013 (Appendix I). In early 2013, we had to remove the experimental warming and cooling treatment plots due to sporadic snowfall (which could break the structures). This removal of treatments did not likely affect growth of Kincaid's lupine as the plants were dormant at that time.

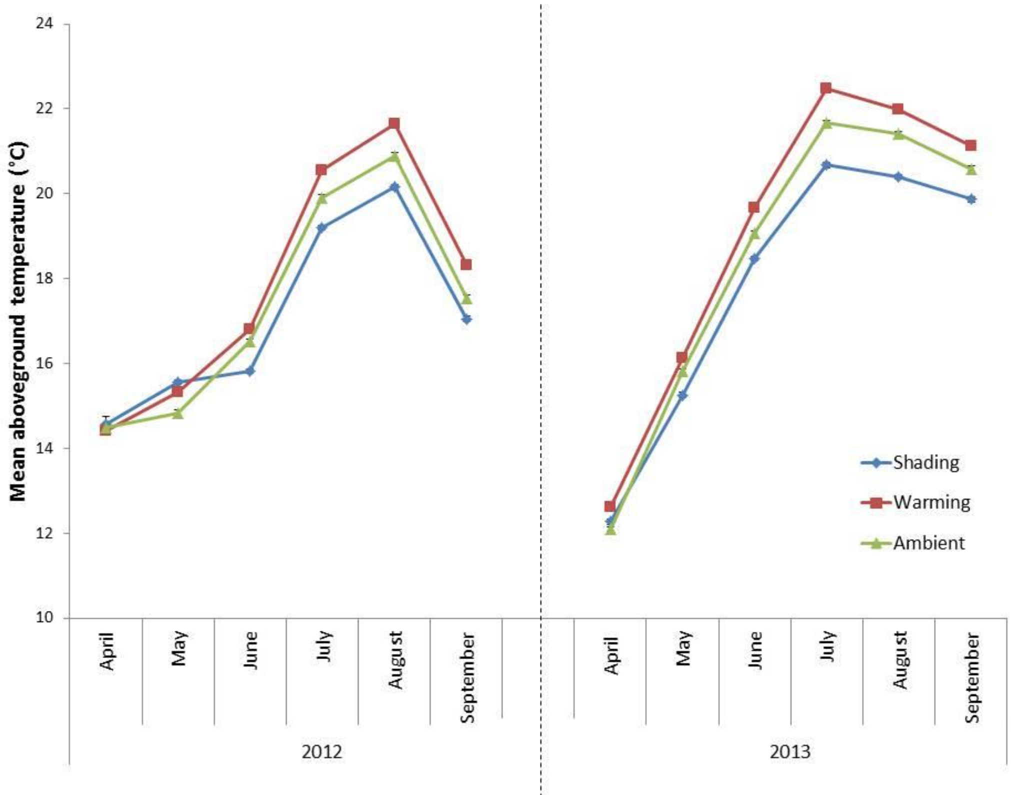

Figure 8. Mean aboveground temperature (°C) in ambient, shading, and warming experimental plots during the Kincaid's lupine growing season in 2012 and 2013. Error bars (present but not visible) represent ± 1SE.

We sought to increase and decrease temperature in treatment plots as compared to the ambient conditions to replicate past, present, and future climate. Across the entire study (minus Jan-March 2013 where treatments were absent) mean temperature in warming treatments was 16.7 °C while that in the shading treatments was 15.8 °C, with mean ambient plots averaging 16.1°C. Our experimental warming and shading treatments were most effective during the spring and summer, which was the growing season of plants (April-September, Figure 8). During the growing season, both the warming and shading plots differed from ambient plots by ± 0.5°C. While our plots exerted temperature differences relative to ambient conditions, the difference was less extreme than that predicted by climate models suggesting an increase of 1 to 2 °C by 2040. During fall and winter (September through March), the temperature differences between the experimental plots and ambient conditions lessened, suggesting that solar radiation was not strong enough to exert temperature differences on the plots. The timing of these differences was very important; to have treatment effects present during the growing season ensured that the treatments were affecting the plants when growth was the most prevalent. The lack of treatment differences during the dormant season should not affect growth of the plants, however it could have unforeseen influences on timing of re-emergence. Plots experienced extreme temperatures ranging from 42°C (June warming plot max) to -6.5°C (ambient January min; Appendix J). These temperatures were much more extreme than those experienced at a local weather station less than a quarter mile away

(OSU Hyslop Farm, Oregon Climate Service; Appendix J). The more extreme temperatures experienced at the experimental plots could be due to the exposed nature of the site which frequently experienced high winds and offered relatively no shelter or shade.

Shading plots tended to have the greatest relative humidity over the course of most of the study (mean = 80.9), and the warming plots having the lowest relative humidity (mean = 78.9) as compared to the ambient plots (mean = 80.4). Though the means across all months differed only slightly, relative humidity was more divergent during the growing season of Kincaid's lupine (April-September), similar to patterns in temperature. As with the precipitation and temperature data, the removal of the treatment plots from January–March 2013 due to inclement weather resulted in the convergence of the humidity data.

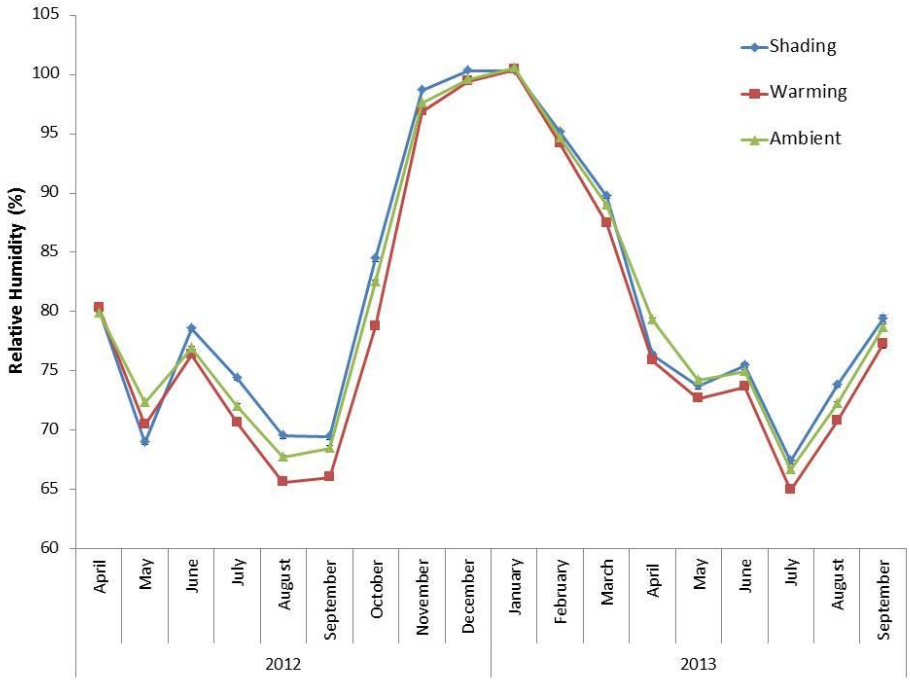

Figure 9. Mean relative humidity (%) in ambient, shading, and warming treatment plots Error bars (present but not visible) represent ± 1SE.

Effects of seed source and treatment on Kincaid's lupine growth

Height of Kincaid's lupine at the common garden ranged from 0.3 cm (Washington) to 39.3 cm (Coburg Ridge), with a mean height of 14.3 cm across all plots. We found mean height differed significantly by seed source, regardless of experimental treatment ($p < 0.0001$, Appendix B). Though there were differences in mean height between seed sources, there were no obvious patterns in height in relation to the proximity of seed sources or their extent in the range of Kincaid's lupine (Figure 10, Table 2). For example, plants from China Ditch (Douglas County recovery zone) were larger than most, along with those from Wren (Corvallis West recovery zone), and McMinnville (Salem West recovery zone); all of these seed sources are scattered throughout the Willamette Valley and do not represent a specific habitat type (partial shade or open).

Interestingly, those plants from source populations in close proximity to each other tended to differ from each other in size (Appendix H). For example, China Ditch and Dickerson Heights (both from Douglas County recovery zone) are disjunct from the rest of the populations which occur in the Willamette

Valley/Puget Trough, however plants from these populations were not similar in height (Figure 10). Seeds from these populations were similar germination time; they germinated far earlier than those from the other populations (Figure 7), most likely as a result of adaptation to a shorter growing season (Figure 3). Plants from Dickerson Heights and Lafayette both were shorter in stature than the majority (Figure 10).

We noticed qualitative differences between seed sources in the common garden, particularly in color, leaf shape and pubescence (Appendix H). For example, plants from Coburg Ridge tended to be much more hairy than the others. These differences show to broad range in physical characteristics of Kincaid's lupine, and demonstrate possible adaptations to the local environment.

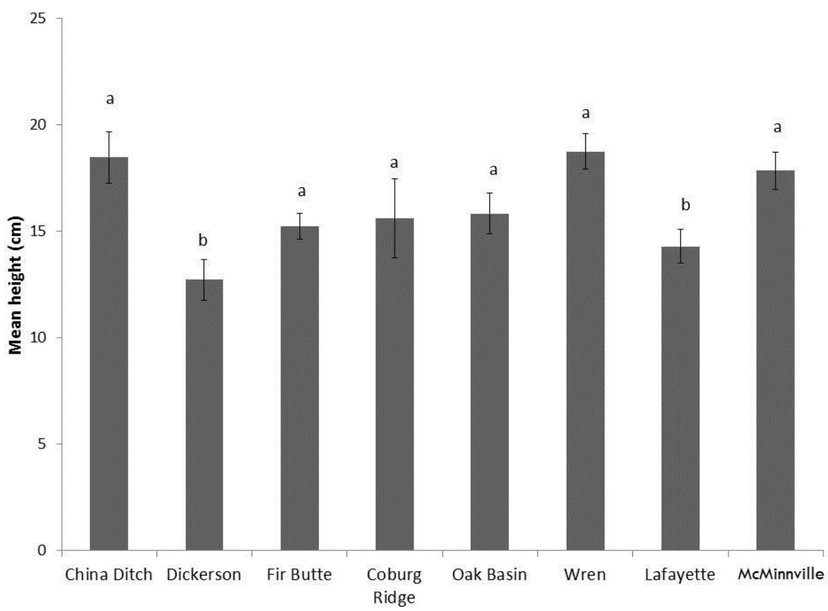

Figure 10. Mean height (cm) of Kincaid's lupine by seed source (presented in order of latitude from south to north). Error bars represent 1 SE. Means with different letters differed in pairwise comparisons (p <0.10).

Though we found no significant treatment effects associated with height of Kincaid's lupine, we did observe some interesting trends that are noteworthy (Figure 11). Plants from China Ditch tended to be taller in height in the ambient plots than the warming and shading treatments, while those from Dickerson Heights had virtually no difference between treatments. Interestingly, plants from the Willamette Valley in the center of its range tended to respond favorably to the warming treatment (Figure 11); while differences were not statistically significant, those from Coburg Ridge, Oak Basin, and Wren (mid-Willamette Valley) tended to have taller plants in the warming treatments. Plants in the northern-most seed sources in Oregon (Lafayette and McMinnville) tended to be taller in the shading treatments, as expected, though these differences were not statistically significant. Plants from Washington were in their first year of growth but were also looking somewhat similar in their trends to the northern populations, as expected (Figure 11).

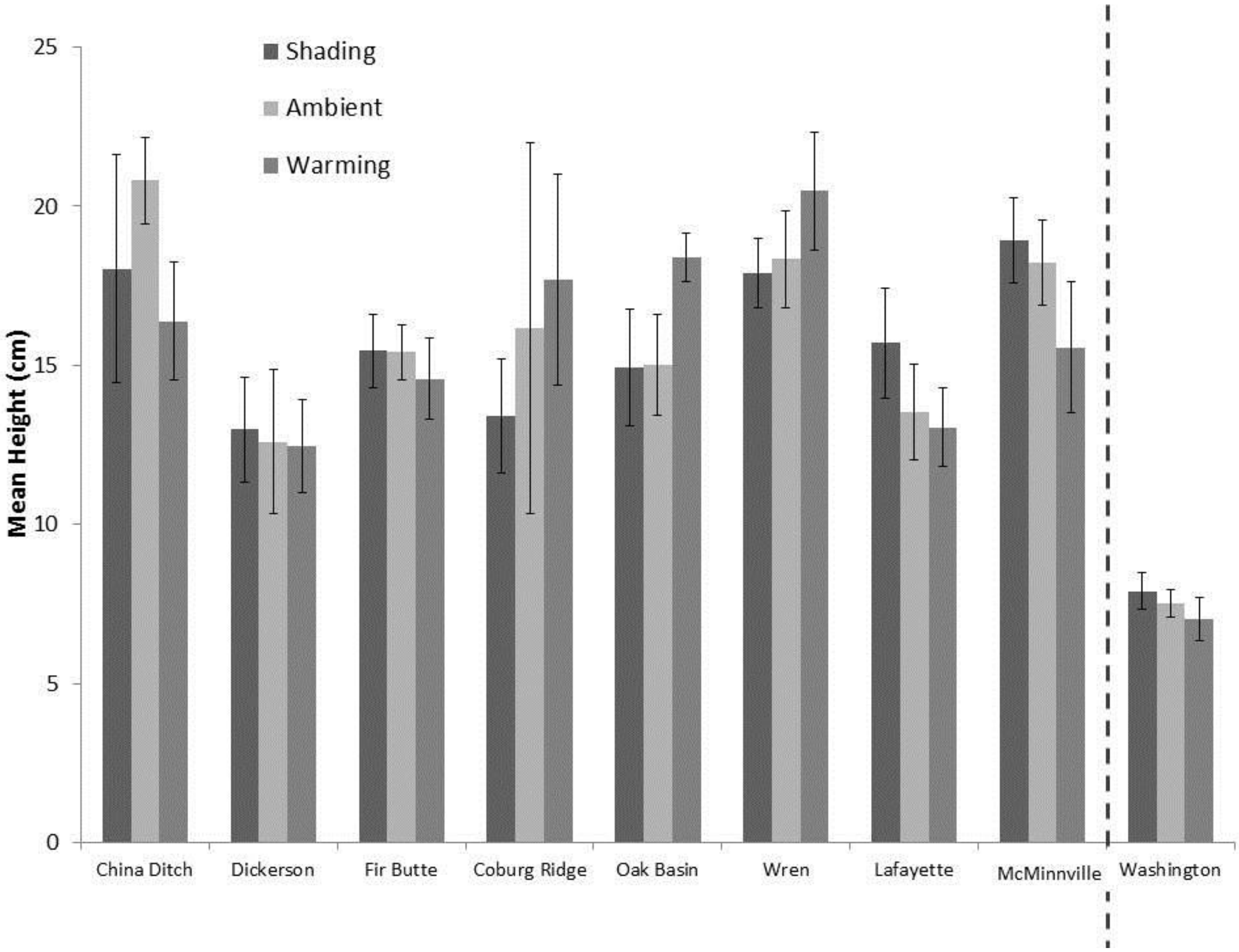

Figure 11. Mean height (cm) of Kincaid's lupine by treatment for each seed source in 2013. Error bars represent 1 SE. Note: Washington plants were one year younger than all other populations represented.

Table 2. Growth and survivorship characteristics for Kincaid's lupine in the common garden, June 2013.

	Ambient			Shading			Warming		
	Mean Height (cm)	Mean number of leaves	Survival from '12 to '13	Mean Height (cm)	Mean number of leaves	Survival from '12 to '13	Mean Height (cm)	Mean number of leaves	Survival from '12 to '13
China Ditch	20.8	61	13	18.0	36	8	16.4	36	13
Dickerson	12.6	30	6	13.0	26	10	12.5	25	8
Fir Butte	15.4	60	13	15.5	36	13	14.6	49	9
Coburg Ridge	16.2	53	5	13.4	30	9	17.7	81	8
Oak Basin	15.0	36	7	14.9	32	8	18.4	49	5
Wren	18.3	53	18	17.9	29	22	20.5	63	15
Lafayette	13.5	30	10	15.7	32	12	13.8	35	19
McMinnville	18.2	38	11	18.9	36	13	15.6	22	8
Washington	7.5	3	23	7.9	4	33	7.0	3	27
Average	14.8	38	106	14.1	25	128	13.9	35	112

Height of Kincaid's lupine and number of leaves were related but not in a strictly linear fashion (Figure 12); there seemed to be a lag time where small plants remain short with few leaves before reaching their full height. All seed sources were represented throughout the range of sizes; those with larger individuals (tall with many leaves) also had individuals that were much smaller with fewer leaves (Figure 12). Those from Washington remained small because it was their first year of growth.

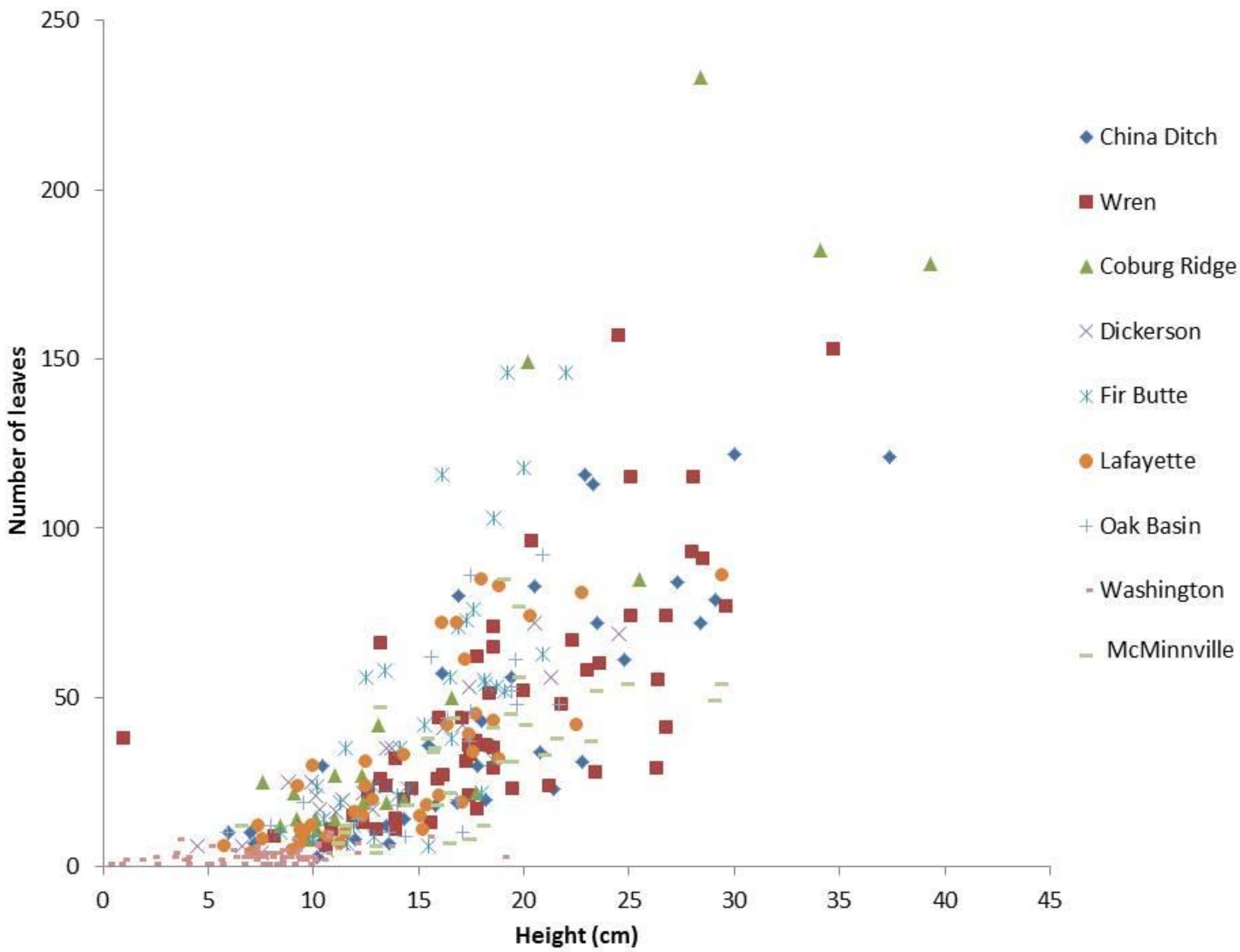

Figure 12. Relationship between number of leaves and height (cm) of individual Kincaid's lupine plants at the common garden. Points represent plants in all experimental treatment plots. Note: Washington plants were one year younger than all other populations represented.

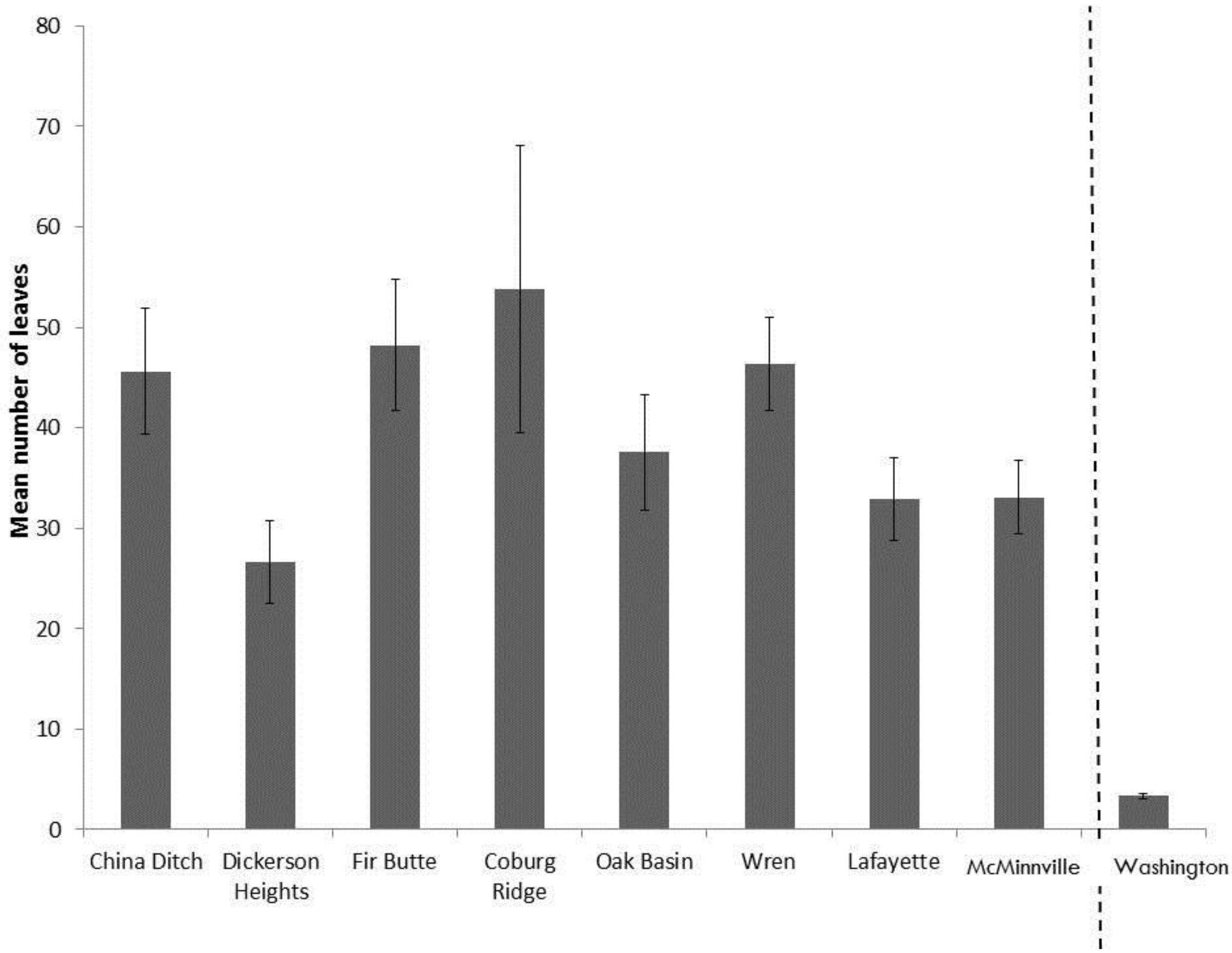

Figure 13. Mean number of leaves for each seed source in 2013. Error bars represent 1 SE. Note: Washington plants were one year younger than all other populations represented.

Number of leaves in 2013 ranged from 3 (China Ditch) to 233 (Coburg Ridge; Figure 12, Figure 13). Plants from Coburg Ridge and Wren tended to have the greatest number of leaves, while those from China Ditch had the fewest (disregarding those from Washington). Number of leaves differed significantly by seed source (p =0.02, Figure 13, Appendix D), and experimental treatment (p = 0.005, Appendix E), though the differences were independent of each other. Many seed sources had similar response in two treatments but a different response in the other (Figure 14). For example, plants from McMinnville (northernmost Oregon source) responded most favorably to the ambient and shading treatments but had fewer leaves in the warming treatments (Figure 14). Plants from China Ditch (the southernmost extent of its range) had more leaves in the ambient plots than in the warming or shading (Figure 14). Number of leaves per plant tended to have large variation between treatment plots, which is evident by the large overlapping error bars (Figure 14). Similar to trends in height, mid-Willamette Valley seed sources (Coburg Ridge, Oak Basin, Wren, and Lafayette) tended to have greater number of leaves in the warming treatments than the other treatments, though these differences were not significant. Though plants from Washington had very few leaves in comparison to others because they were in their first year of growth, the shading treatment had slightly more leaves than the ambient or warming treatment; data in future years will enable us to further understand potential treatment effects on the northernmost seed source.

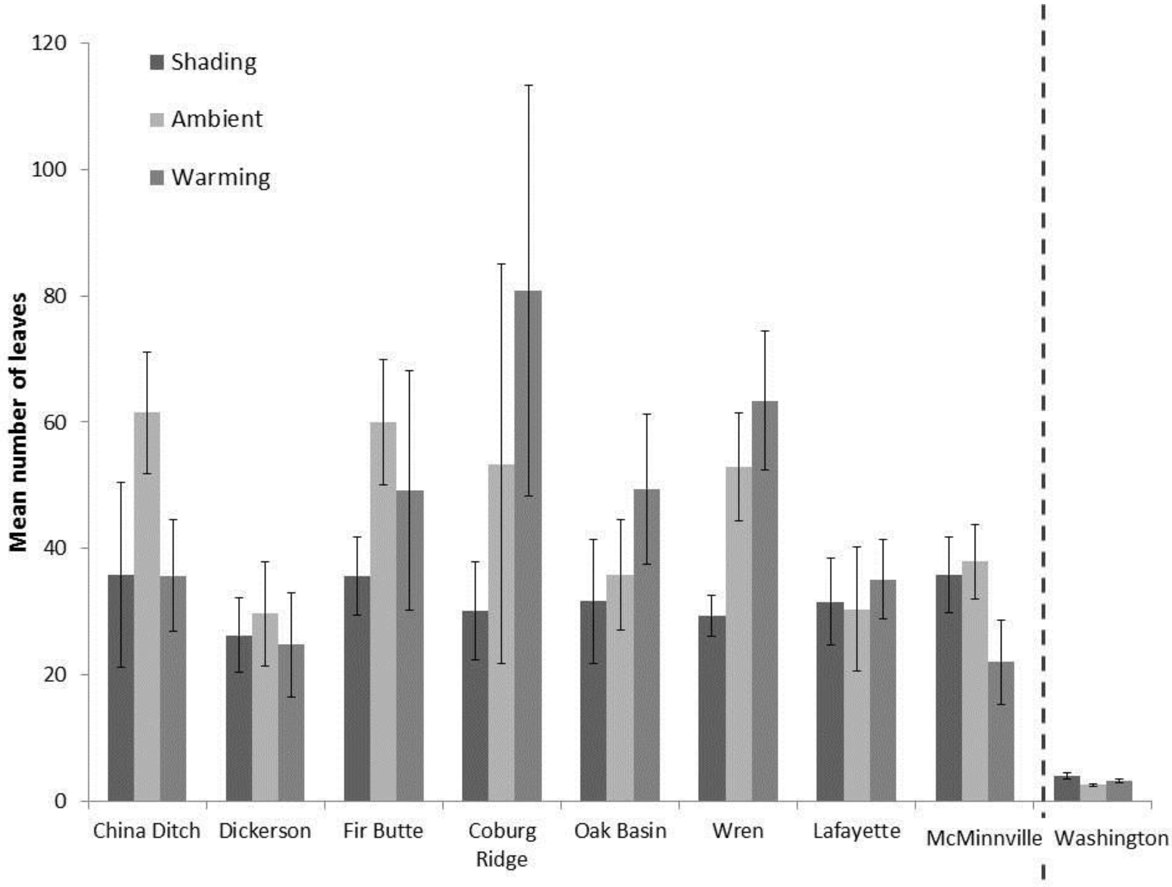

Figure 14. Mean number of leaves per Kincaid's lupine in ambient, shading, and warming treatment plots. Error bars represent 1 SE. Note: Washington plants were one year younger than all other populations represented.

Effects of seed source and treatment on Kincaid's lupine survivorship and reproductive effort

Proportions of survivorship from April 2012 (out-planting) to monitoring (June 2012) ranged from 0.7 to 0.9 (Figure 15). Plants from China Ditch, Dickerson Heights, Fir Butte, Wren, and Lafayette all had very high survivorship (0.8-0.9 range), whereas proportions of survivorship from Coburg Ridge, Oak Basin, and McMinnville were in the 0.7-0.8 range. Proportions of survivorship dropped dramatically from June 2012 to June 2013. Plants from Wren had the greatest survivorship (proportion = 0.5), while all other seed sources had much lower survivorship, ranging from 0.2 to 0.3. Plants from Washington had moderate survivorship in its first year (April 2013-June 2013) (proportion = 0.7), however for the first year of growth this was at the low end of survivorship when compared to those from the other seed sources. This is likely because in 2012 we did an initial screening of those plants that had experienced mortality and replaced those that needed replacing in early May 2012 (20% of the initial out-planting). This accounted for initial mortality not from treatments but from the stress of out-planting. We had no extra plant material for the Washington seed source and could not make similar replacements in 2013.

We found differences in survivorship (those plants alive in 2013) relative to seed source ($p = 0.002$) but not to treatment ($p = 0.57$, Appendix F). All seed sources experienced high mortality between 2012 and 2013 (Figure 15). Wren had the highest proportion of survivorship (0.5), followed by Lafayette (0.33). Dickerson Heights and Coburg Ridge both had the lowest survivorship between 2012 and 2013 (0.20 and 0.21, respectively). Interestingly, while Coburg Ridge also had the lowest survivorship in the greenhouse, plants from Dickerson Heights had the highest levels of greenhouse survivorship (Figure 7); greenhouse survivorship and survivorship at the common garden were unrelated.

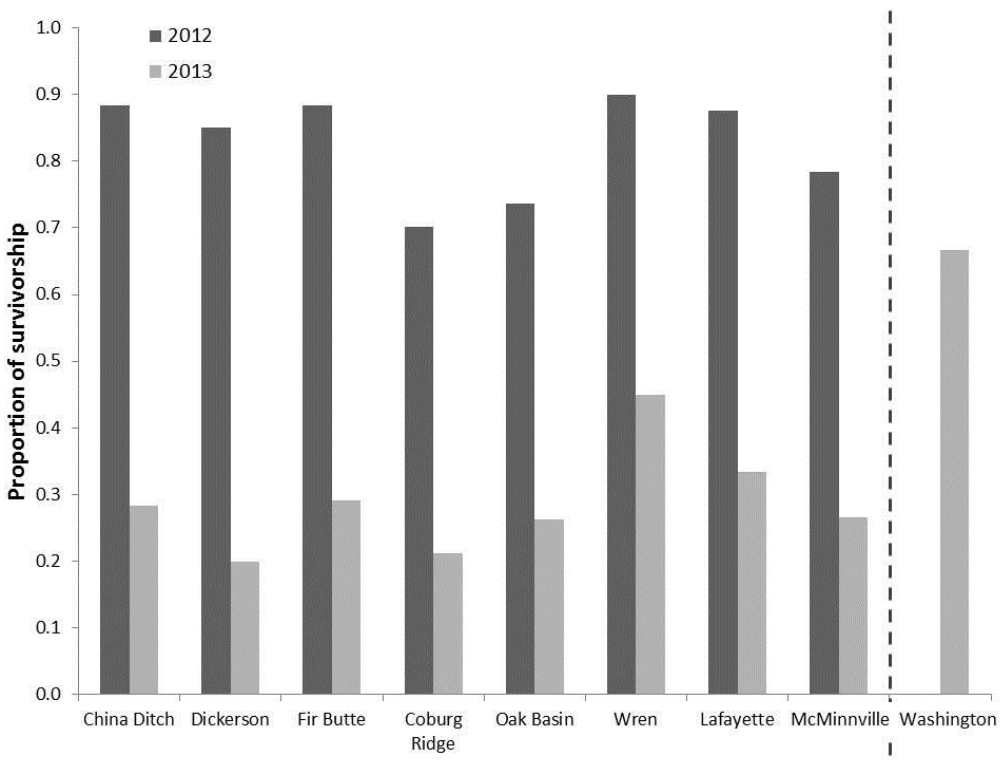

Figure 15. Proportion of survivorship in 2012 and 2013. Note: Washington plants were added in 2013.

Reproductive effort in 2013 (at the time of monitoring) varied between seed sources (Figure 16). Numbers reported indicate only the effort at the time of monitoring (June 2013), and do not include racemes that formed after that time. All racemes over the course of the study were discarded to ensure no cross pollination between seed sources. Proportions of reproductive plants ranged from 0 (Lafayette and Dickerson Heights) to 0.21 (China Ditch). Of those plants that were reproductive, number of racemes per plant ranged from 11 to 1. Interestingly, plants from seed sources in close geographic proximity varied greatly in reproductive effort; China Ditch had 32 total racemes whereas plants from Dickerson Heights (both Douglas County recovery zone) had none. Wren had the most racemes at the time of monitoring (42). While Dickerson Heights had no racemes, Oak Basin and Lafayette also had very few (2 each), though these seed sources were not reproductive at the time of monitoring, there is a chance that they produced racemes after that time. Future tracking reproductive effort across the entire growing season will enable us to provide a more complete view of fecundity by seed source and potential treatment effects as well as any phonological differences in time of flowering.

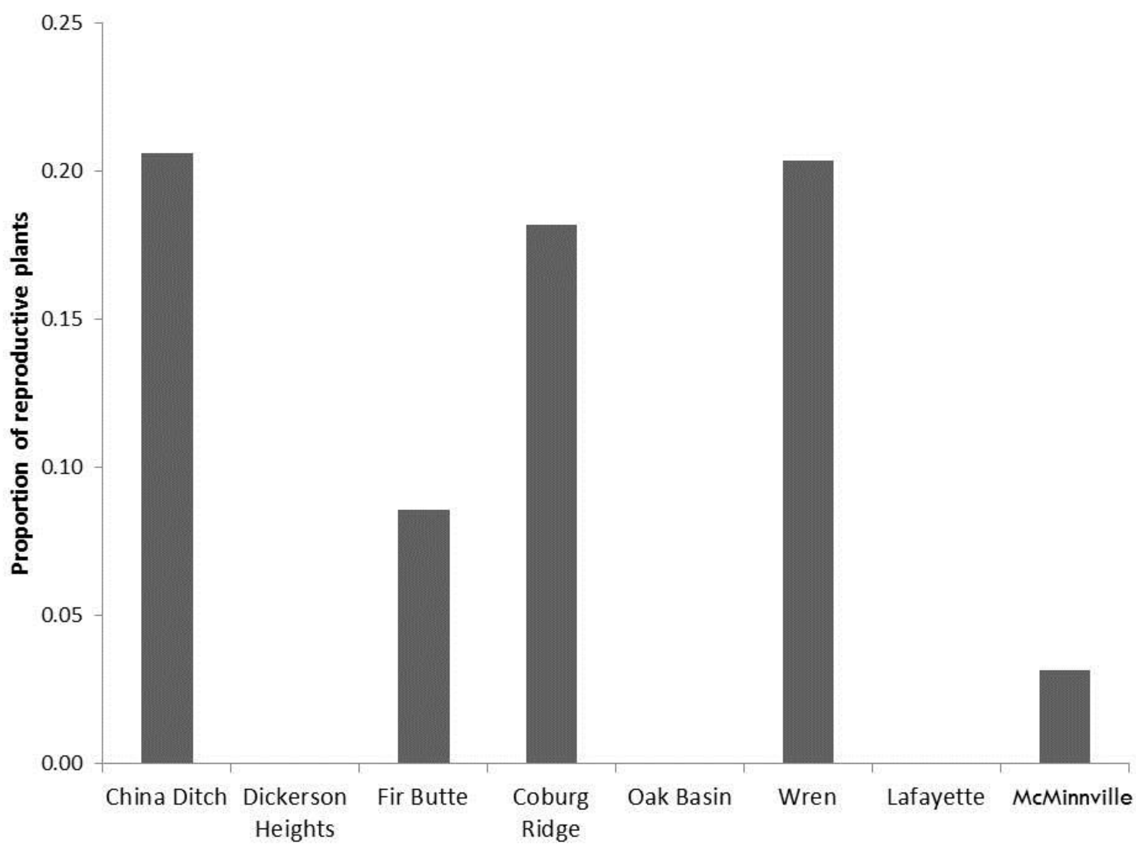

Figure 16. Proportion of reproductive plants by seed source in June 2013.

Student and Volunteer Involvement

Volunteers have been an integral part of this study contributing time for design and structure building, greenhouse propagation, out-planting, weeding, precipitation monitoring, watering, and site maintenance. In total, 101 volunteers participated in this study, contributing 412 hours. In the process, each of these individuals has actively taken part in learning about climate change, native plants, and the considerations necessary for perpetuation of rare species.

Figure 17. Mario Carbajal, OSU SEEDS student and long-term volunteer, setting up the common garden plots in the snow (March 2012)

We worked with middle and high school volunteers from the City of Corvallis Youth Volunteer Corps to help build the experimental plots and to aid with weeding. Students from Oregon State University volunteered their time as part of the Geo 300 "Sustainability for the Common Good" course, and helped with potting Kincaid's lupine and greenhouse maintenance. One student with the OSU SEEDS program (Strengthening Education and Employment for Diverse Students) volunteered his time to design and set up the experimental plots (Figure 17).

The project reached students in a special needs class at South Albany High School. Students received hands-on learning opportunities about native plants, plant ecology, and climate change impacts. IAE staff from the Ecological Education Program provided three classroom lessons over the 2012-13 school years. In addition, students participated in two visits to the common garden where they weeded the plots while learning about competition for resources, and aided in collection of data on Kincaid's lupine size (Figure 18). This project provided unique hands-on service learning opportunities where students gained practical problem solving skills, as well as further developed their sense of place and understanding of the value of functioning ecosystems and changes in our climate.

Figure 18. Volunteers participating in A. structure building (City of Corvallis Youth Volunteer Corps), B. greenhouse propagation (OSU Geo 300 students), C. precipitation monitoring (OSU student Miles Penk), D. data collection (South Albany High School students), and E. plot weeding (City of Corvallis Youth Volunteer Corps).

DISCUSSION

With current and ongoing climate change, land managers face many challenges regarding the preservation of rare species and the habitats they reside in. Though climate models have projected potential changes including warmer summers and wet winters in the Pacific Northwest (Parson 2001, Doppelt et al. 2009), land managers must incorporate uncertainty and adaptability into future habitat management (Bachelet et al. 2011). To mitigate for future climate changes, new considerations regarding seed source may be appropriate when conducting habitat restoration or introductions of rare species to new habitats. Regional scale considerations of utilizing the full range of habitat tied with local scale considerations of microhabitats might enable the perpetuation of species that have the ability to adapt to changes in climate (Bachelet et al. 2011). Assisted colonization, while controversial, may be necessary to expand potential habitat for rare species and aid in their preservation.

We tested nine seed sources of Kincaid's lupine in a common garden setting under ambient, experimental warming, and experimental shading conditions to replicate past, present, and future climate change. Results should be interpreted cautiously as data collection occurred in the second year of growth and this study only took place at one location; establishing additional sites would enable us to see if these trends are consistent across multiple environments. Plants from all recovery zones persisted in the common garden under all treatment conditions, suggesting that they are all able to tolerate temperature and humidity conditions outside those of their respective local habitats. We found that seed source had an effect on all responses measured: the height of Kincaid's lupine, number of leaves, and survivorship. We even saw differences among seed sources early in the phenology of the plant where various sources germinated at different times, as well as differences in reproductive effort among seed sources. In addition, number of leaves was dependent upon not only seed source but also experimental treatment, though not the interaction of the two factors. These results suggest that Kincaid's lupine has phenotypic variability between seed sources (Figure 3), but also indicates potential to thrive under conditions that maximize those traits. For example, plants from the Willamette Valley tended to have greater number of leaves in the warming treatments than in the ambient or shading treatments. Of course, a species' ability to tolerate warmer conditions could be due to the microhabitats of their respective sites; most plants from these sites grew in full sun which may have contributed to their tolerance to warmer conditions.

We hypothesized that plants from the Douglas County recovery zone would be better adapted to warmer conditions, since they experience warmer temperatures than those in the Willamette Valley (Figure 3). Plants from China Ditch did not respond in this way, where plants had greater number of leaves in the ambient treatments, and while plants from Dickerson Heights had slightly more leaves under ambient conditions, these treatment effects weren't significant. Plants in the Douglas County recovery zone grow in very different conditions than those from the Willamette Valley where many populations are in very shrubby areas or along roadsides, as opposed to the open prairie conditions experienced by the other seed sources. These differences in source habitat could explain the lack of response to the warming treatment, where they might be more adapted to utilizing shade in their local environments. Plants from Fir Butte, the southernmost site in the Willamette Valley, also responded most-favorably to the ambient treatment for number of leaves, though this difference was not significant. Plants from Coburg Ridge, Oak Basin, and Wren (all mid-Willamette Valley) tended to respond favorably to the warming treatment, both in number of leaves and height. On the other hand, the hypothesis also stated that those in the northernmost extent of its range might do more favorably in the shading treatments, than in the warming or ambient given that they are adapted to cooler conditions. Plants from Lafayette and McMinnville had slightly taller plants in the shading treatment however these differences were not statistically significant. Though plants from Washington were only in their first year of growth, they tended to respond positively to the shading treatment, which was consistent with our hypothesis. Some of these trends, while noteworthy, were not found to be statistically significant; data from another year of growth would be necessary to tease about these patterns and see if treatment effects become more prominent over time. We collected data on reproductive effort at the time of monitoring and results suggest that it varied by seed source, and of those that were reproductive, the number of racemes per plant varied greatly. Data from 2014 will yield a greater understanding of the effects of the treatments on size of Kincaid's lupine, survivorship, and also fecundity over time.

We experienced low survivorship at the common garden over the course of this study. Though numbers were high in 2012, there was a large decrease in survivorship by 2013. The environmental conditions at the site were very harsh and transplants were left to the elements immediately after out-planting which could have added to stress of the propagules. We also experienced a summer drought followed by a more dry winter than in previous years. Survivorship in this study was low, but was also similar to that in other out-plantings in 2012 (J. Getty, *personal communication*), suggesting that annual variability in climate could have had an effect. While survivorship was low, plants from all seed zones persisted into their second year, suggesting that of those that survived, they were able to tolerate a wide range of conditions. Future studies in a more natural environment and at multiple sites may enable better survivorship and the ability to differentiate more clear treatment effects.

Though this study suggested population differentiation in growth in response to climate, there were many factors that could have affected the results noted. The site of the common garden was extremely exposed and experienced very harsh environmental conditions including high winds. The extreme conditions maximum and minimum temperatures at the common garden were much more extreme than those at a nearby weather station suggesting the relative harshness of this site (Appendix J). Likewise, the area selected for this site was an old agricultural field that was used to produce grass seed, resulting in extremely compressed soils which may not be representative of how these species would grow in the wild. Competition from weeds present at the site may have had a large impact on growth and survivorship of Kincaid's lupine. Weeds at the common garden were widespread and abundant, and created a gradient across the treatment plots. For example, plots on the west side of the common garden had high percent cover of wild radish (*Raphanus* sp.) whereas those on the east side had higher cover of clover (*Trifolium* sp.). While we weeded around each of the plants, the differences in competition for nutrients due to differences in the competitive environment could have significantly affected growth of Kincaid's lupine. Though our experimental treatments increased and decreased temperature relative to ambient conditions, the difference in temperature (± 0.5 °C) were not as extreme as anticipated warming (1 to 2 °C by 2040, Doppelt et al. 2009). Plant responses to these treatments might become clearer if treatments produced more divergent differences in temperature.

There are many unknowns associated with a species' response to projected warmer temperatures associated with climate change. We tested for response to experimental warming and found that some seed sources responded favorably. Likewise, plants from all seed sources survived and persisted, suggesting that Kincaid's lupine is able to tolerate conditions outside that of their local environment and that there is potential for use of different seed sources in any future assisted colonization. To prepare for future unknowns, land managers must approach conservation on varying scales, both local and regional (Bachelet et al. 2011). Our study suggests that Kincaid's lupine may be able to persist across a more regional scale, enabling land managers to make those decisions when necessary. If assisted colonization is necessary, we have identified that Willamette Valley seed sources (Coburg Ridge, Oak Basin, Wren, and Lafayette) responded favorably to the experimental warming treatment.

This study was an example of a small-scale effort to understand the potential response of a rare species to climate change. This study also serves as a model for the involvement of volunteers in scientific research. Each person that participated was educated on the goals of the study and genuinely wanted to help with climate change research. To quote one high-school volunteer, participation in this study was valuable "because I learned to deal with others; because I learned how plants become endangered, and because I learned to kill weeds from the roots." Each individual who participated took away their own unique perspective and will hopefully consider their role in climate change and the importance of conservation.

Future studies that focus on different rare species and addition of replicates at multiple sites throughout the species' range could greatly increase our understanding of potential management considerations in the face of climate change. Continuing this study for at least one more year would enable us to analyze more data on size, survivorship, and reproductive effort of Kincaid's lupine to see if treatment effects become more obvious, as there could be a lag time of the plants' response to such treatments. By continuing monitoring, we will be able to make comparisons between the Washington seed source (northernmost population) and the others (in the 2nd year of growth) to see if plants respond to the experimental treatments. More intensive monitoring of phenology of the species could greatly increase understanding of the phenological response of each source and if experimental warming or cooling influences its phenology. The differences in germination time between seed sources suggests that the seed sources vary phenologically, and more intensive monitoring of dates of re-emergence within treatment plots, and timing of raceme formation could yield interesting and important information regarding the species' ability to persist under different climate conditions. This information would be imperative for efforts centered around the Fender's blue butterfly and its need for host plants under project climate conditions.

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APPENDICES

Appendix A. Analysis of variance (ANOVA) table for the response of height (cm) of Kincaid's lupine in 2013 predicted by treatment and seed source (omitting plants from Washington).

	Df	SS	MS	F value	*P* value
Treatment	2	23.4	11.7	0.4	0.71
Seed source	7	1070	152.9	4.6	**<0.0001**
Treatment: Seed source	14	408.1	29.2	0.9	0.59
Residuals	238	7960.7	33.5		

Appendix B. Analysis of variance (ANOVA) table for the response of height (cm) of Kincaid's lupine in 2013 predicted by seed source(omitting plants from Washington).

	Df	SS	MS	F value	*P* value
Source	7	1088	155.4	4.7	**<0.0001**
Residuals	254	8375	33.0		

Appendix C. General linear model (quasipoisson errors) for the response of number of leaves predicted by seed source (omitting plants from Washington).

	Df	Deviance	Residual Df	Residual Deviance	*P* value (Chi)
Treatment	2	312.33	259	6430.5	**0.002**
Source	7	460.23	252	6070.3	**0.01**
Treatment:Source	14	422.5	238	5647.8	0.26

Appendix D. General linear model (quasipoisson errors) for the response of number of leaves predicted by treatment (omitting plants from Washington).

	Df	Deviance	Residual Df	Residual Deviance	*P* value (Chi)
Treatment	2	312.3	259	6530.5	**0.005**

Appendix E. General linear model (quasipoisson errors) for the response of number of leaves predicted by seed source (omitting plants from Washington).

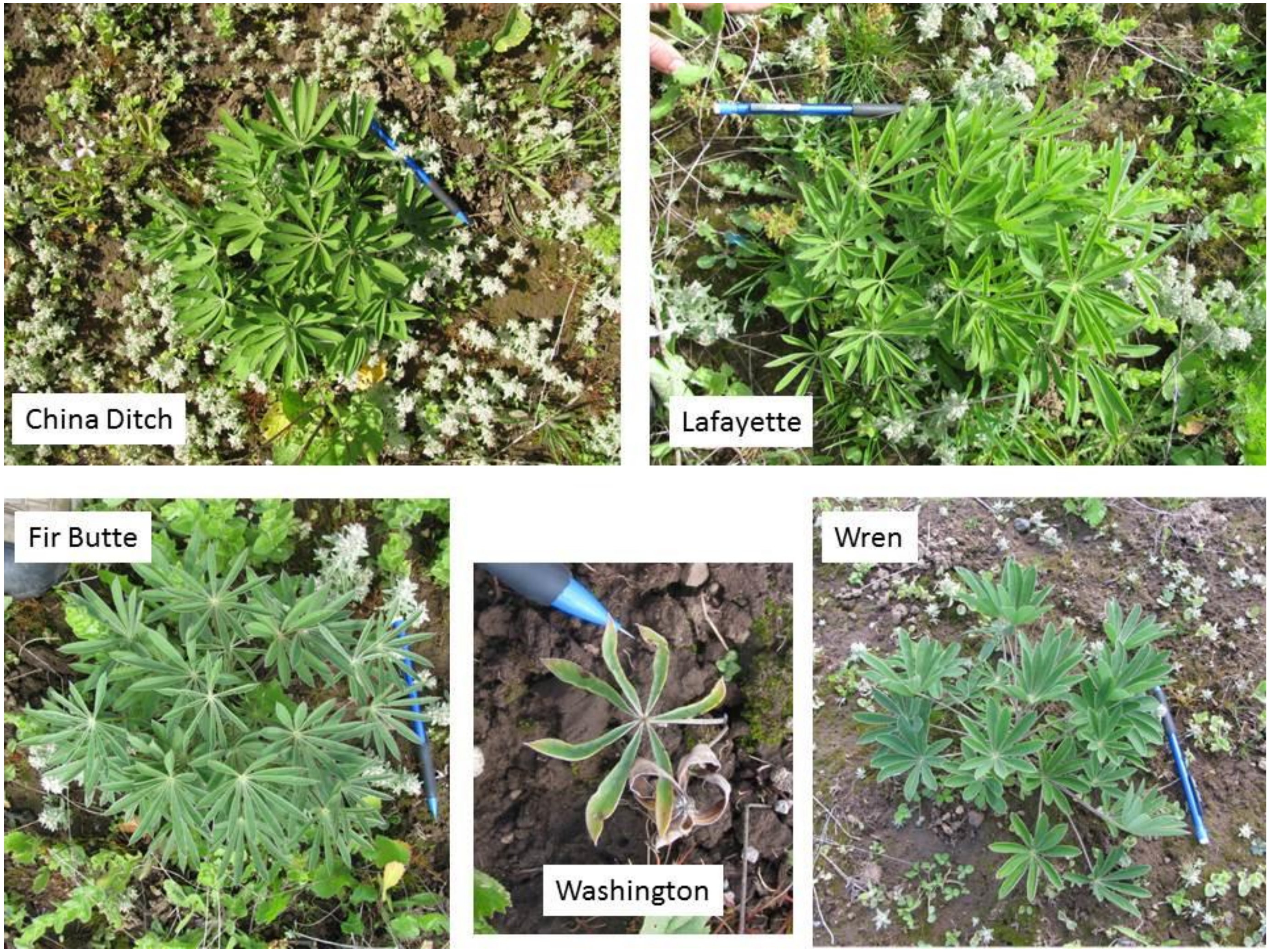
	Df	Deviance	Residual Df	Residual Deviance	*P* value (Chi)
Source	7	462.9	254	6379.8	**0.02**

Appendix F. General linear model (binomial) for the response for survivorship from 2012-2013, predicted by treatment and seed source (omitting plants from Washington).

	Df	Deviance	Residual Df	Residual Deviance	*P* value (Chi)
Treatment	2	1.12	897	1070.0	0.57
Source	7	23.12	890	1046.8	**0.002**
Treatment:Source	14	13.3	876	1033.5	0.50

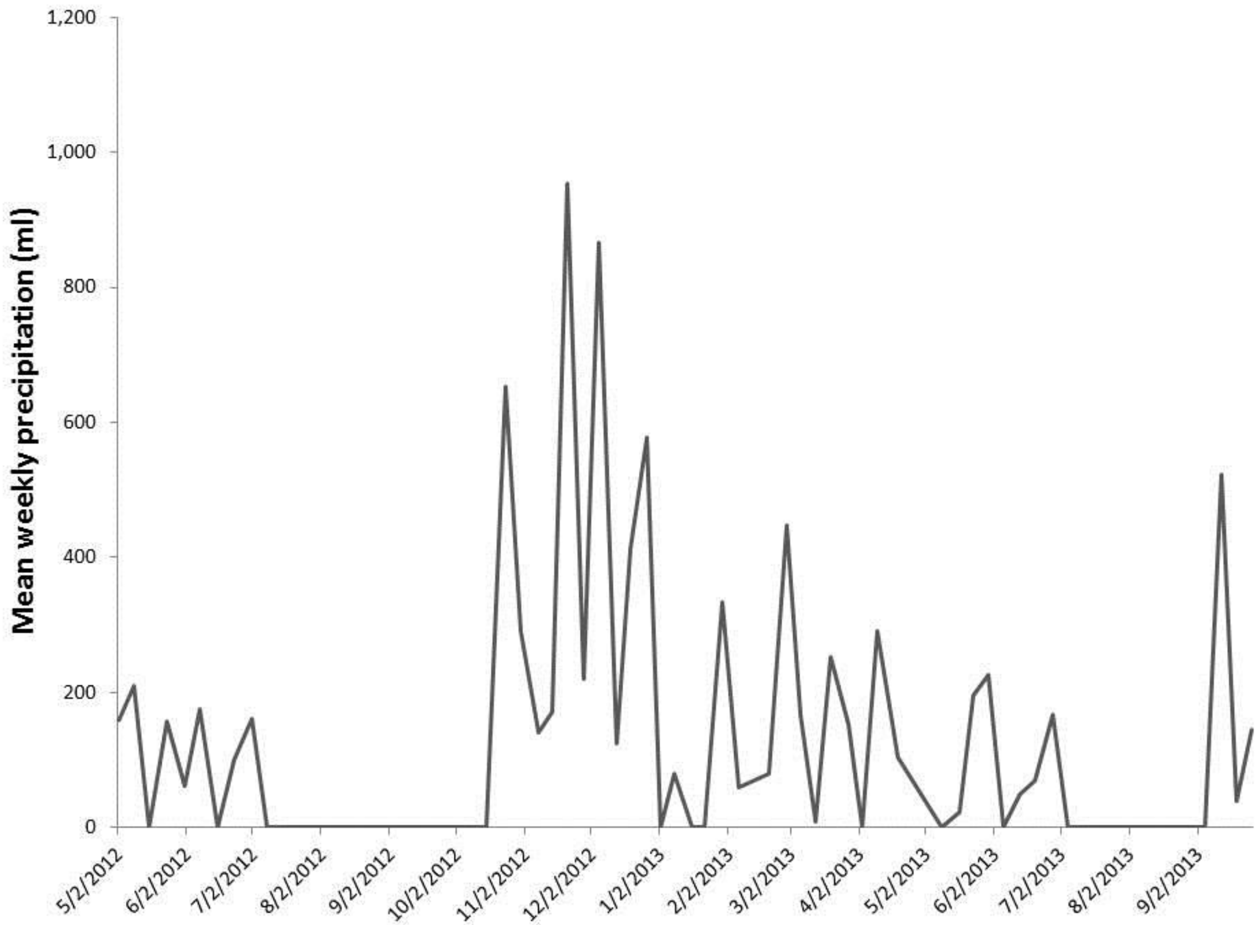
Appendix G. General linear model (binomial) for the response for survivorship from 2012-2013, predicted by treatment and seed source (omitting plants from Washington).

	Df	Deviance	Residual Df	Residual Deviance	*P* value (Chi)
Source	7	23.1	892	1048.0	**0.002**

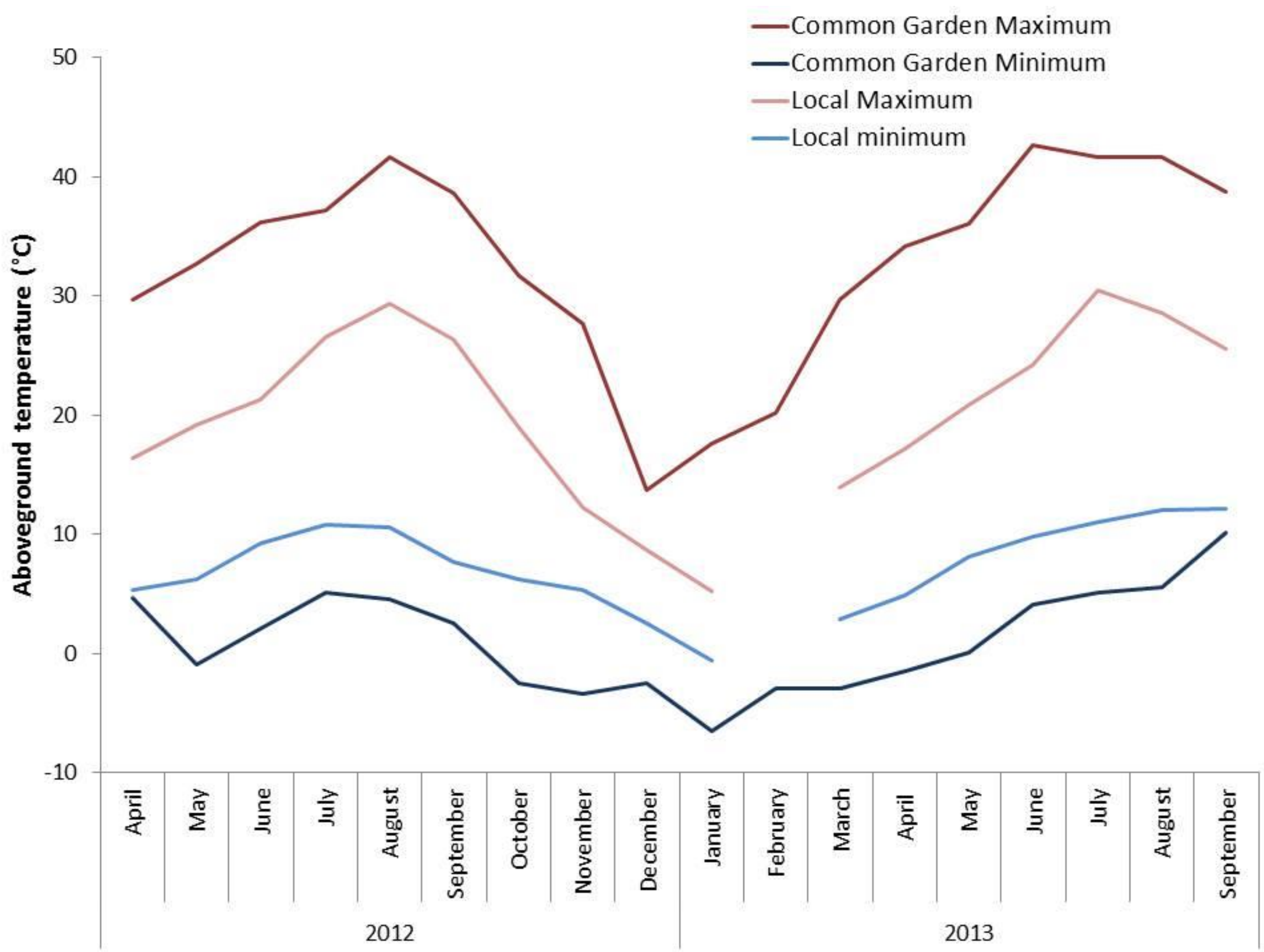


Appendix H. Images of Kincaid's lupine by seed source. All were out-planted in 2012 except for Washington which was out-planted in 2013.

Appendix G. Continued.



Appendix I. Mean weekly precipitation in ambient conditions at the common garden experiment.



Appendix J. Maximum and minimum temperature at the common garden, along with local maximum and minimum temperature for a weather station on the OSU Hyslop farm (Oregon State University 2013). Note: Temperature data unavailable at the OSU Hyslop farm for February 2013.